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SYNTHETIC AND OBSERVATIONAL STUDY OF Pn EXCITATION AND PROPAGATION IN CENTRAL ASIA

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13. ABSTRACT *(Maximum 200 words)*

More than one hundred Pn spectra from central Asia have been collected. The nonlinear spectral inversion method of Xie (1993) was modified to reduce effects of deviations of sources, paths and sites from idealized theoretical models. To estimate Pn geometrical spreading, synthetic calculations of Pn propagation in central Asia were conducted using 1D velocity models. The results show that a model of $\Delta_0^{-1}(\Delta_0/\Delta)^m$, with m between 1.3 to 1.5, is roughly valid, but deviations in Pn amplitude from that model can be a factor of 2. The observed Pn amplitude in central Asia are strongly affected by 3D structural complications and source radiation patterns. Pn amplitude across the Kyrghistan network (KNET) from sources located in and around the Lop Nor Test Site is highly variable (by a factor of about 20), despite the small aperture of the KNET (~ 2 °). The amplitude variation is not due to a systematic variation in site responses, but is likely due to deep-seated 3D structural complications, such as a complex Moho topography. Pn amplitudes across KNET from some Northern Xinjiang earthquakes are much weaker than from the Lop Nor explosions, making Pn/Lg ratio an effective discriminant. The performance of the discriminant varies with varying focal mechanisms and path configurations.

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ABSTRACT

This report summarizes my research on excitation and propagation of regional waves, mainly Pn, in the past year. The nonlinear spectral inversion method of Xie (1993) was modified to better estimate source and path spectral parameters using Pn and Lg. The modification was made to further reduce effects of deviations of sources, paths and sites from idealized theoretical models used in the inversion. An extensive attempt was also made to estimate the Pn geometrical spreading term in reasonable 1D structures for central Asia. Synthetic calculations of Pn propagation in central Asia were conducted using three recently published 1D velocity models. The results typically show that a $\Delta_0^{-1}(\Delta_0/\Delta)^m$, with m ranging between 1.3 to 1.5, is roughly valid, but one should expect localized deviation of Pn amplitude from that model by at least a factor of 2.

We have collected more than one hundred Pn spectra from broad-band seismic stations in central Asia. Pn amplitude across the Kyrghistan network (KNET) from sources located in and around the Lop Nor Test Site is found to be highly unstable. Despite the small aperture of the KNET (~ 2 °), the time domain Pn amplitude varies by as much as a factor of 19. Spectral analysis reveals that the amplitude variation primarily occurs at low frequencies (~ 1hz). Due to the pronounced topographic variation near the stations, frequency-dependent polarization analysis yields little information on the origin of the amplitude variation. Analysis of Pn propagating through the network in different directions, on the other hand, suggests that the amplitude variation is not due to a systematic variation in site responses. The more likely cause of the amplitude variations is deep-seated 3D structural complications, such as a topographic variation at the Moho. We demonstrate that a 2D Moho topography, likely associated with the drastic tomographic variation in the earth's surface east of the KNET, could have preduced a ray pattern that quantitatively gives rise to the observed Pn amplitude anomaly.

Pn amplitudes at KNET stations from some Northern Xinjiang earthquakes are much weaker than from the nearby Lop Nor explosions, making Pn/Lg ratio an effective discriminant between these particular earthquakes and underground nuclear explosions. The weak Pn amplitude from these earthquakes are likely caused by a null in the Pn radiation pattern of the earthquakes involved, whose mechanisms are likely dominated by an east-west strike slip motion. Therefore, it might be misleading to extrapolate the low Pn/Lg amplitude ratio to earthquakes with other source-station configurations. For the earthquakes that occurred in southern Tien Shan, for example, observed Pn amplitudes at the KNET stations are typically quite high. This is consistent with higher Pn radiation patterns predicted for focal mechanisms that are predominantly reverse slip, which is typical for earthquakes in southern Tien Shan.

Research so far demonstrates that the Pn amplitude in central Asia are affected significantly by 3D structural complications and source radiation patterns. Any attempt to utilize Pn in discriminating explosions from earthquakes, or in characterizing source/path properties, must account for these complications. An extensive analysis is underway to

compare the stability of spectral inversion using Pn alone with that jointly using Pn and Pn coda (or Pg), which is expected to be more stable than Pn.

1. INTRODUCTION

Lg and Pn are two of the most prominent regional phases used in the discrimination of explosions from earthquakes. Xie (1993) developed a nonlinear inverse method to simultaneously estimate the seismic moment (M_0), corner frequency (f_c) and path-variable Q_0 and η (Q at 1 hz and its power-law frequency dependence, respectively) using the Lg spectra from both explosions and earthquakes. The method was applied to 21 underground nuclear explosions (Xie, 1993; Xie *et al.*, 1996) and 53 earthquakes (Cong *et al.*, 1996) in central Asia. Major findings of these studies include (a) The Lg Q values at 1 Hz for numerous paths in central Eurasia were found to agree rather well with those predicted using a tomographic Lg coda Q map (Xie & Mitchell, 1991). (b) For both underground nuclear explosions and the earthquakes studied, the logarithm of Lg M_0 values correlate linearly with the body wave magnitude (M_b), with slopes of slightly greater than 1.0. (c) The Lg M_0 values tends to scale scale with $f_c^{-\alpha}$, with the value of α ranging between about 3.6 to 4.0. (d) The scaling between Lg M_0 and f_c values for the explosions, estimated using the earthquake source model (*i.e.*, the ω^2 source model without spectral overshoot, often known as the Brune's model), differ from that between the Lg M_0 and f_c values for the earthquakes. The main difference between the two scalings is that for a given M_0, the explosions tend to have higher f_c values. This suggests that the Lg from explosions has a richer high-frequency content, as compared to Lg from earthquakes. This phenomenon appears to be systematic in central Eurasia, and appears to be opposite to that observed in the western U.S. It thus raises a question on the transportability of any explosion discriminant based on the Lg spectral content alone.

The main objective of this research is to extend the inverse method of Xie (1993) to analyze Pn spectra from both explosions and earthquakes. The analysis should yield Pn source M_0, f_c, and path Q_0, η values. These values will advance our fundamental understanding on how the excitation and propagation of Pn differ from those of Lg. By comparing the $M_0 \sim f_c$ scalings derived using Pn from explosions and earthquakes with those derived using Lg, we will investigate if, when and why the Pn/Lg ratio works as an discriminant between explosions and earthquakes.

This research is composed of several tasks. The first is to develop a relatively reliable and robust method to measure the source M_0, f_c, and path Q_0, η values using the Pn phase. This task is difficult not only because of the complication in estimating M_0, f_c values due to the source model dependence, as we have discovered for the inversion of the Lg spectra, but also because of the effects of non-isotropic source radiation pattern and 3D path structural complexities in the Pn spectra. The second task of this research is to analyze, with the method developed, Pn spectra from many events to obtain their M_0 and f_c values, as well as the Pn Q_0 and η values for various regions such as central Asia and middle-east. The third task is to compare the $M_0 \sim f_c$ scalings for earthquakes and explosions, derived using Pn, with those derived using Lg, to obtain the differences in those scalings. In this report, we summarize major accomplishments of this research

achieved over the past year.

2. MODIFICATION OF THE INVERSE METHOD

§ 2.1 Practical problems affecting the spectral inversion

High-frequency regional seismograms are affected by many factors, ranging from non-isotropic source radiation pattern, 3D structural complications along the paths, site amplification and occasional instrument miscalibrations. Quantifying these effects in deterministic manner is impractical due to the many degrees of freedom involved. To study Lg spectral characteristics, Xie (1993) adopted the stochastic modeling used by Street *et al.* (1975), Herrmann and Kijko n (1983), Xie & Nuttli (1988) and Sereno *et al.* (1988). In the stochastic modeling $A_i(f)$, the Lg or Pn spectra at an ith station, is modeled as

$$A_i(f) = S(f, \theta_i) G(\Delta_i) \exp\left(- \frac{\pi f \Delta_i}{V_g Q_i(f)} \right) X_i(f) \ , \tag{1}$$

where f is frequency, θ_i, Δ_i, and $Q_i(f)$ are the azimuth, distance and quality factor of Lg or Pn from the source to the ith station. V_g is the mean group velocity of Lg or Pn, $X_i(f)$ is the site response at the ith station, and $S(f, \theta_i)$ is the source-to-Lg (or Pn) spectral radiation in the direction of θ_i, or source spectrum, which can be represented by

$$S(f, \theta_i) = \begin{cases} \dfrac{M_0 R(\theta_i)}{4\pi \rho v^3} \dfrac{1}{1 + f^2 / f_c^2} & \text{for } \textit{earthquakes} \\ \dfrac{M_0 R(\theta_i)}{4\pi \rho v^3} \dfrac{1}{\left[1 + (1 - 2\beta) f^2 / \ f_c^2 + \beta^2 f^4 / \ f_c^4 \right]^{1/2}} & \text{for } \textit{explosions} \end{cases} \ , \tag{2}$$

where M_0 and f_c are seismic moment and corner frequency, For Lg spectra ρ and v are the averaged crustal density and shear wave velocity; for Pn they are the source-zone density and compressional wave velocity, respectively. $R(\theta_i)$ is the azimuthally varying source radiation pattern. In the above equation, we have used the omega-square model without overshoot for the earthquakes (often referred to as the "Brune's model") and the omega-square model with overshoot for the explosions (the modified Mueller-Murphy model; Sereno *et al.*, 1988). $G(\Delta_i)$ in Eq (1) is the geometrical spreading factor and typically has the form

$$G(\Delta_i) = \Delta_0^{-1} (\Delta_0 / \Delta_i)^m \tag{3}$$

where Δ_0 is a reference distance, and m is the decay rate of $A_i(f)$ at large distances ($\Delta > \Delta_0$). Typical values of Δ_0 and m are about 100 km and 0.5 for Lg (Street *et al.*, 1975), and about 1 km and 1.3 for Pn (Sereno *et al.*, 1988). In the next section we will

further discuss the values of Δ_0 and m for Pn in central Asia. $Q_i(f)$ in Eq (1) is the apparent Q (quality factor),

$$Q_i(f) = Q_{0i}\ f^{\eta_i} \tag{4}$$

where Q_{0i} and η_i are apparent Q to the ith station at 1 Hz and its power-law frequency dependence, respectively. To develop a practical algorithm for inverting spectral characteristics of regional wave excitation and propagation, Xie (1993) made an important assumption that for a given explosion event, $R(\theta_i)$, Δ_0 and m in Eq (2) and (3) are not, but Q_{0i} and η_i are, station-variable. Cong *et al.* (1996) extended this assumption to Lg from earthquakes. When estimating M_0, f_c, Q_{0i} and η_i values, this assumption may well cause bias. However, I think that for modern, broad-band seismic stations, a reasonable estimate of the variation in Lg spectra caused by the combined effect of the station variable $R(\theta_i)$, $X(f)$, Δ_0 and m and the instrument malfunction is within about a factor of 2. At large epicentral distances (roughly $\Delta > 2.8\ V_g\ Q(f)\ /\ (\pi f)$), the error caused by this effect is virtually ignorable. At smaller distances, however, there are indications that this effect may cause significant error in Q_0 and η estimate. Cong *et al.* (1996), for example, did not use Lg spectra from stations with smaller distances (< about 650 km) since the resulting Q_0 and η values are too inconsistent with those previously found for central Asia.

Another source of error of the spectral inversion of Lg, Pn and any other high-frequency phases comes from the tendency for individual source spectra to deviate from the idealized stochastic models in Eq (2). Xie *et al.* (1996) found that the values of M_0, f_c resulting from inverting Lg spectra of 21 underground nuclear explosions are dependent on which of the source models in Eq (2) was used, despite that the high-frequency asymptotes of the two models were similar. Recently Xie (1996) also found that the M_0, f_c values estimated for the 1995, Western Texas earthquake ($M_W \sim 5.7$) are dependent on the source model used. Since the estimates of M_0, f_c and path Q values are dependent on the source model used, a deviation of the source spectra of any event from the idealized source model used in a spectral inversion will undoubtly cause bias in the estimated M_0, f_c, Q_0 and η values.

These biases are expected to be more serious when one deals with Pn. This is because that (1) The distance range for Pn observation is between about 2 to 12°, which is significantly narrower than about 2 to 35°, the distance range for Lg observation. Therefore the condition of $\Delta > 2.8\ \ V_g\ Q(f)\ /\ (\pi f)$ is less frequently satisfied for Pn. (2) Pn is primarily comprised of only one ray, as against many rays comprising the Lg. Pn is thus more vulnerable to the effects of non-isotropic $R(\theta_i)$. (3) The geometrical spreading of Pn, even in simplified 1D media, is less stable than that of the Lg (Section 3 of this report; also *c.f.* Sereno & Given, 1990, Zhu *et al.*, 1991).

§ 2.2 *Modifications of the algorithm*

To reduce these bias for simultaneous determination of source M_0, f_c, and path Q_0, η, we have recently made two modifications to the non-linear inverse algorithm of Xie (1993). To present the modification, we recall that in the method of Xie (1993), a range of combinations of M_0 and f_c values as the possible solution are exhaustively examined. For each such combination, we calculate the synthetic source spectra $S(f)$ using Eq (2), and thereby calculating a quantity A''_{ij}, defined as

$$A''_{ij} = -\frac{V_g}{\pi\Delta_i}\ln\left(\frac{A_i(f_j)}{S(f)G(\Delta_i)}\right) \quad . \tag{5}$$

where f_j is the jth discrete frequency. The mathematical expectation of $\ln(A''_{ij})$ is

$$\ln\left(A''_{ij}\right) = (1-\eta_i)\ln f_j - \ln(Q_{0i}) \quad , \tag{6}$$

therefore we may estimate the Q_i and η_i values, corresponding to the given M_0 and f_c values, by a linear regression fitting using Eq (6). This enable us to find one set of possible model vector,

$$\mathbf{m} = (M_0, f_c, Q_{01}, \eta_1, Q_{02}, \eta_2, \cdots Q_{0N}, \eta_N)^T \quad , \tag{7}$$

where N is the total number of stations recording the event. For each possible set of solutions, we may estimate a residual, which is defined as

$$Res^2 = \sum_{i=1}^{i=N}\sum_{j=1}^{j=J(i)} \varepsilon_{ij}^2 \quad , \tag{8}$$

where $J(i)$ is the total number of spectral estimates available for the ith station, and ε_{ij} is defined as

$$\varepsilon_{ij} = \ln\left[G^{-1}(\Delta_i)A_i(f_j)\right] - \ln\left[S(f_j)\exp\left(-\frac{\pi f_j^{1-\eta_i}\tau_i}{Q_{0i}}\right)\right] \quad . \tag{9}$$

The residual, Res^2 is a function of $\mathbf{m}$. By comparing Res^2 calculated for all of the possible $\mathbf{m}$, we find the optimal $\mathbf{m}$ which gives the minimum of all residuals.

At the ith station, the combined effect of the station variable $R(\theta_i)$, $X_i(f)$, Δ_0, m and the instrument malfunction/miscalibration may raise or deduce $A_i(f)$ by an amount that is most likely within a factor of 2 (Xie & Mitchell, 1990; Cong *et al.*, 1996). In addition, the randomness in $A(f)$ causes it to fluctuate up and down at localized frequencies. At close-in stations (say $\Delta_i < V_g Q_i(f)/(\pi f)$), where the effect of amplitude reduction due to finite Q is not yet very pronounced, A''_{ij} may well be less than zero at localized frequencies (this is the well-known "negative Q" problem in Q studies). In the method of Xie (1993), even if negative A''_{ij} occurs at very localized frequencies, mathematical singularities will occur when the right-hand side of Eq (5) is estimated, and the corresponding $\mathbf{m}$ will then be rejected as a reasonable solution. This could occur even when the overall trend of $A''_i(f)$ can still be fit by a reasonable combination of Q_{0i} and η_i, *via*

$$A''_{ij} = \frac{f_j^{1-\eta_i}}{Q_{0i}} \quad , \tag{10}$$

This motivated me to make the first modification of the method of Xie (1993). In the modified algorithm, for a possible combination of M_0 and f_c values, A''_{ij} are calculated as before. When at any ith station one or more negative A''_{ij} values occur, the Q_{0i} and η_i values are fitted directly using A''_{ij} (Eq (10)), rather than using $\ln(A''_{ij})$ (Eq (6)), using a iterative, non-linear least square algorithm (Eq (12.159) of Aki & Richards, 1980). If the resulting Q_{0i} and η_i values are reasonable, the corresponding **m** is saved as a possible solution. In using both synthetic and real Lg or Pn data, I have found that when there are stations which are close to the source and are associated with higher Q values, such that $\Delta_i < V_g Q_i(f)/(\pi f)$, the modified algorithm is able to find the optimal **m** models that were rejected by the unmodified method of Xie (1993) due to localized fluctuations in A''_{ij}.

The second modification to the algorithm of Xie (1993) is that when additional information on source spectra obtained by using the empirical Green's function (EGF) method, or on two-station Q by measuring two-station spectral ratios are available, the spectral inversion for optimal **m** incorporates these information. For example, if an seismic event is recorded by stations at varying distances such that two-station pairs may be formed to measure inter-station Q values using the standard spectral ratio technique, then the average two-station Q can be obtained separately, *prior* to the simultaneous non-linear spectral inversion. In the latter inversion, a model vector **m** that minimizes the residual, Res^2, but fails to match either the f_c values from the EGF analysis, or the averaged two station Q_0 and η values obtained earlier, is not considered to be the optimal solution. This is because that the smaller residual may have been an artifact due to non-isotropic source radiation patterns, or due to deviations of source spectra from the idealized stochastic models in Eq (2).

In an application of the modified algorithm to the Lg excitation and propagation from the 1995 western Texas, $M_w = 5.7$ event, Xie (1996) finds that these modifications are very efficient in seeking for a optimal model parameter, **m**, that better describes the spectral characteristics of the Lg excitation and propagation to over twenty broad-band stations in the continental U.S. I expect that the modified algorithm will perform even better for the study of the Pn phase. This is because (1) Pn is more affected by the source radiation pattern due to its simpler ray composition. (2) Pn is more subjected to the effect of spectral fluctuations which cause negative A''_{ij} since for Pn, Δ_i is typically small (less than about 12 °) and V_g typically large (about twice as that of Lg). These make the condition, $\Delta_i < V_g Q_i(f)/(\pi f)$, occur more frequently for Pn. (3) The correction of the geometrical spreading of Pn is much less precise than that of the Lg. When this correction is overestimated,, A''_{ij} will be underestimated and will tend to be negative.

3. SYNTHETIC STUDY OF Pn GEOMETRICAL SPREADING IN CENTRAL ASIA

One of the most uncertain factors in determining the Q and source spectral parameters using Pn is its geometrical spreading term (GST) (*e.g.*, Sereno *et al.*, 1988; Sereno & Given 1990; Zhu *et al.*, 1991). Sereno *et al.* and Zhu *et al.* suggested that the best GST for Scandinavia and Canada are approximately described by Eq (3), with Δ_0 and m being approximately 1 km and 1.3, respectively. We have estimated the GST with synthetic Pn seismograms for central Asia, using a frequency-wave number integration algorithm (Saikia, 1994) and three recently published velocity models for the area. These models are plotted in Figure 1, they include: (1) model M1 of Roecker *et al.* (1993) for northern Tien Shan, (2) the model of Gao & Richards (1994) for the Lop Nor test site, and (3) the model for Kazakhstan by Quin & Thurber (1992). In the calculations, we applied the earth flattening correction (Sereno & Given, 1988). Figure 2 shows the decay of synthetic Pn amplitude spectra between 0.2 and 2.0 hz, calculated using an explosive source embedded at a depth of 1 km, and three velocity models, including (1) model M1 of Roecker *et al.* (1993) for northern Tien Shan, (2) Model of Gao & Richards (1994) for the Lop Nor test site, and (3) Model for Kazakhstan by Quin & Thurber (1992). These models are plotted in Figure 1. In the calculations, we applied the earth flattening correction as suggested by Sereno & Given (1990). The linear regression fitting of the logarithm of the synthetic amplitude decay results in estimates of Δ_0 and m that are summarized in Table 1. For all of the models used, the estimated R_0 is subjected to large uncertainties of factors of 25 to 277. The uncertainty in m estimates are moderate, ranging between about 0.2 and 0.3. Taking these uncertainties into account, the R_0 and m values in Table 1 agree with the values by Sereno *et al.* (1988) and Zhu et al. (1991) for Scandenavia and Canada. In Figure 2, we also indicate the local deviations of the synthetic amplitude from the regressional fit. For all of the three model used, one should expect a local variation of about a factor of 2. This is in contrast to what we found for synthetic Lg amplitude decay (not shown in this report), in which the local deviation is only in the order of 10%. Therefore, the large uncertainties in R_0, m estimates and the large fluctuation in Pn amplitude decay from the regressional trend clearly indicate that an attempt to precisely model Pn GST, even in the simplified 1D cases, is unsuccessful. In practice, this attempt is even more unsuccessful if we take into account that the real structure varies three dimensionally. As of this writing, We plan to used an m of 1.3 and R_0 of 1 km (Sereno *et al.*, 1988) throughout this research.

Table 1. Values of Δ_0 and m from Pn Synthetics

Velocity Model Used	Δ_0	m
M1 (Roecker *et al.*)	23.42 (×/ 29) km	1.43 ± 0.24
Gao & Richards (1994)*	24.1 (×/ 25) km	1.37 ± 0.17
Quin & Thurber	14.1 (×/ 277) km	1.36 ± 0.29

* Used model M1 for mantle below 75 km.

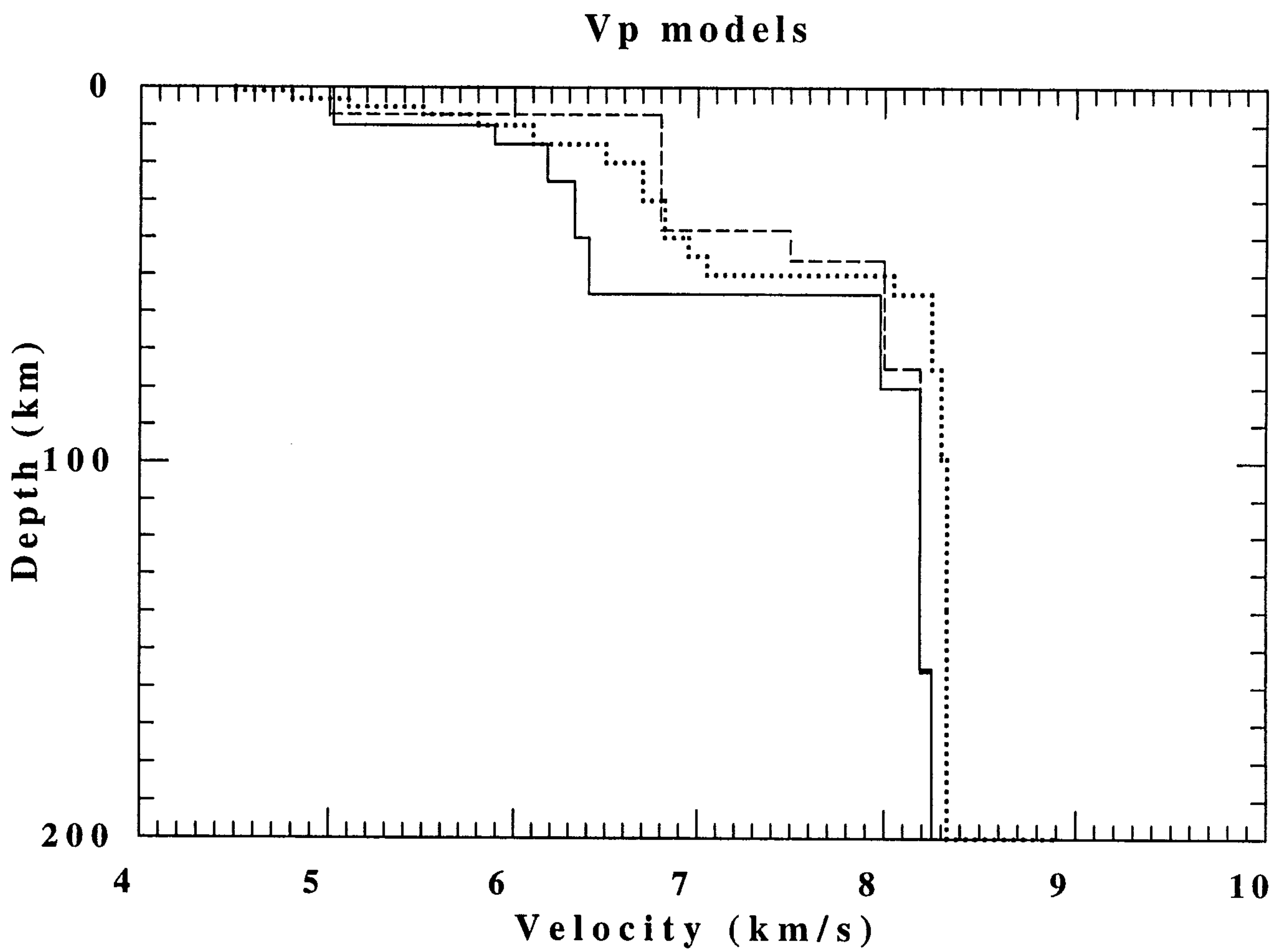

Figure 1. Compressional velocity models used in the Pn synthetics. The solid line is model M1 for Northern Tien Shan by Roecker et al. (1993). The dashed line is the model of Gao & Richards (1994) for the Lop Nor Test Site, combined with model M1 at depths > 75 km. The dotted line is the model by Quin & Thurber (1992) for Kazakhstan.

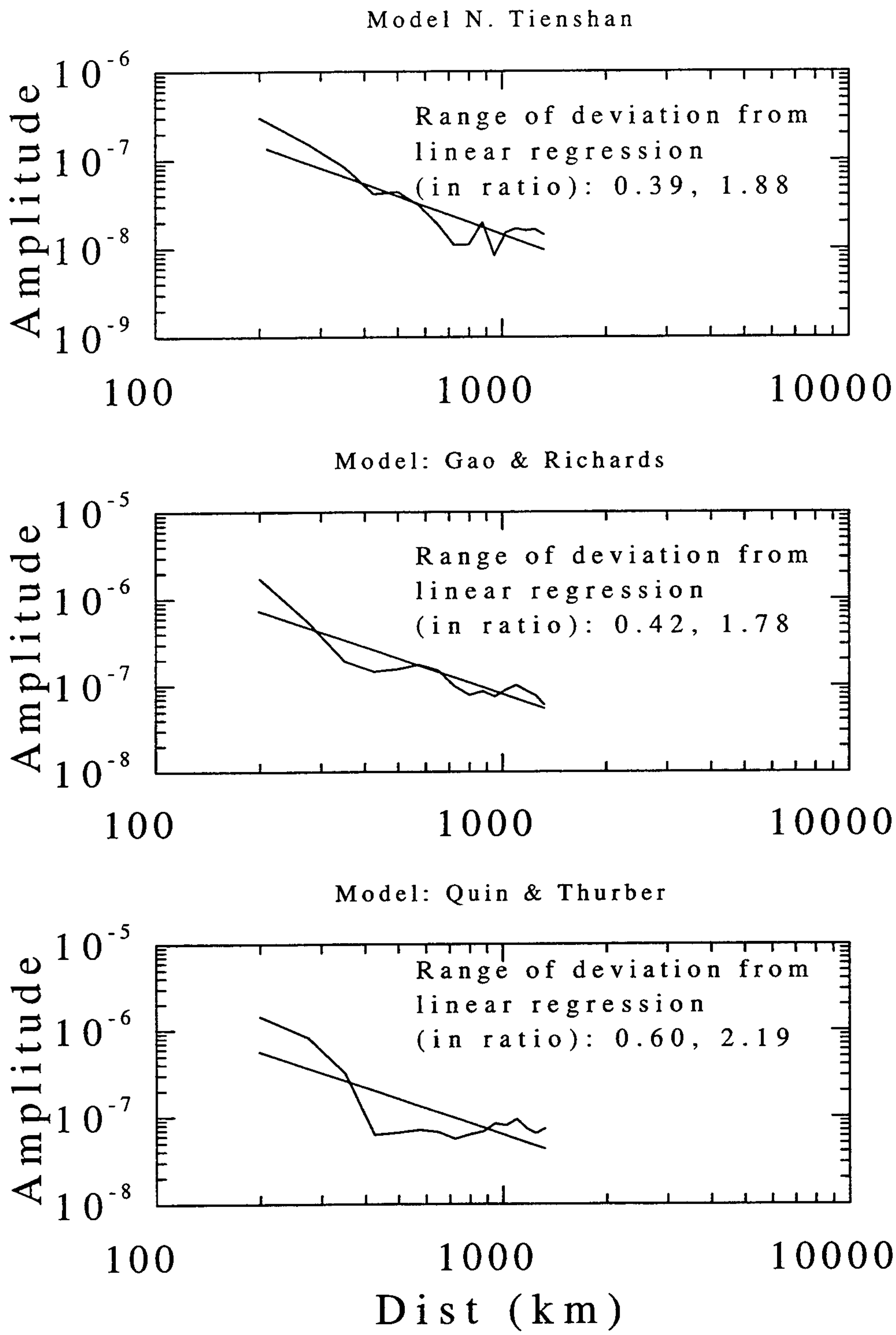

Figure 2. Decay of synthetic Pn amplitude spectra averaged over 0.2 to 2.0 hz, calculated using the velocity models in Figure 1 with infinite Q values. The straight line in each panel is the linear-regression fit of the decay, which gives the estimates of R_0 and m in Table 1.

4. Pn AMPLITUDE VARIATION IN CENTRAL ASIA

We have collected more than one hundred Pn spectra recorded at 16 broad-band IRIS, Kyrghistan network (KNET), Kazakhstan Network (KZN) and CDSN stations, from three underground nuclear explosions and 14 earthquakes in central Asia. A wealth of information have been gained on the characteristics of excitation and propagation of Pn in central Asia. Quantitative inversion for M_0, f_c and path Q have not been conducted to most of the spectra obtained, since we spent most of the last year for algorithm and software development, as well as for understanding the Pn geometrical spreading. We have, however, extensively examined features of time domain and frequency domain Pn amplitude from many earthquakes and several explosions. One important finding if that the Pn amplitude from Lop Nor explosions vary drastically across the KNET stations. As an example, Figure 3 shows the record section from the Oct. 7, 1994 Lop Nor explosion, which is located to the east of the KNET stations (Figure 5). The Pn amplitude varies by a factor of about 19 across the KNET, despite the relative small span (~ 2°) of the network. Figure 4 shows the corresponding amplitude spectra of Pn, obtained using a window with an effective length of 4.5 s. The amplitude variation primarily occur at low (~ 1hz) frequencies. For instance, the 1 hz amplitude is a factor of 27 higher at station KBK than at AML.

Various attempts have been made to explore the origin of this amplitude variation. We studied frequency-dependent polarization of Pn across KNET from Lop Nor explosions, but found that the polarization is strongly affected by the topography near individual stations, thus is not very useful in inferring the origin of the amplitude variation. We studied Pn amplitude across KNET from earthquakes in southern Tien Shan, and found that the pattern of Pn amplitude variation differs from that of Lop Nor explosions. Figure 6 shows a record section from a southern Tien Shan earthquake. In Figure 6, Pn amplitudes at stations KBK and AML are low and high, respectively, opposite to the trend observed in Figure 3. Therefore, a systematic site response is ruled out as the cause of the amplitude variation. We also analyzed Pn from earthquakes in northern Xinjiang, west of Lake Bosten Hu (Figure 5). Figure 7 shows the record section for one of such earthquakes. Generally, Pn is very weak across the KNET, but the pattern of amplitude variation is similar to that found from Lop Nor explosions: Pn amplitude reaches its maximum at stations KBK and KZA and drops to a minimum at more distant stations. This suggests that some 3D velocity anomaly along the east-west oriented paths is responsible for the amplitude variation. Figure 8 shows a synthetic Pn ray pattern through an 1D model, which is adapted from model M1 (last section) by adding a velocity gradient of 2×10^{-3} s/km (before the earth flattening correction) into the uppermost mantle between depths of 50 to 150 km. This ray pattern is stable and unrealistic, since the observed large amplitude variation must be associated with some kind of unstable ray pattern. The easiest way to introduce an unstable pattern is to introduce a 3D topography to the Moho, across which the velocity contract is the most drastic for all boundaries at depth. Figure 9 shows ray pattern in a 2D structure, which is adapted from the 1D structure in Figure 8 by

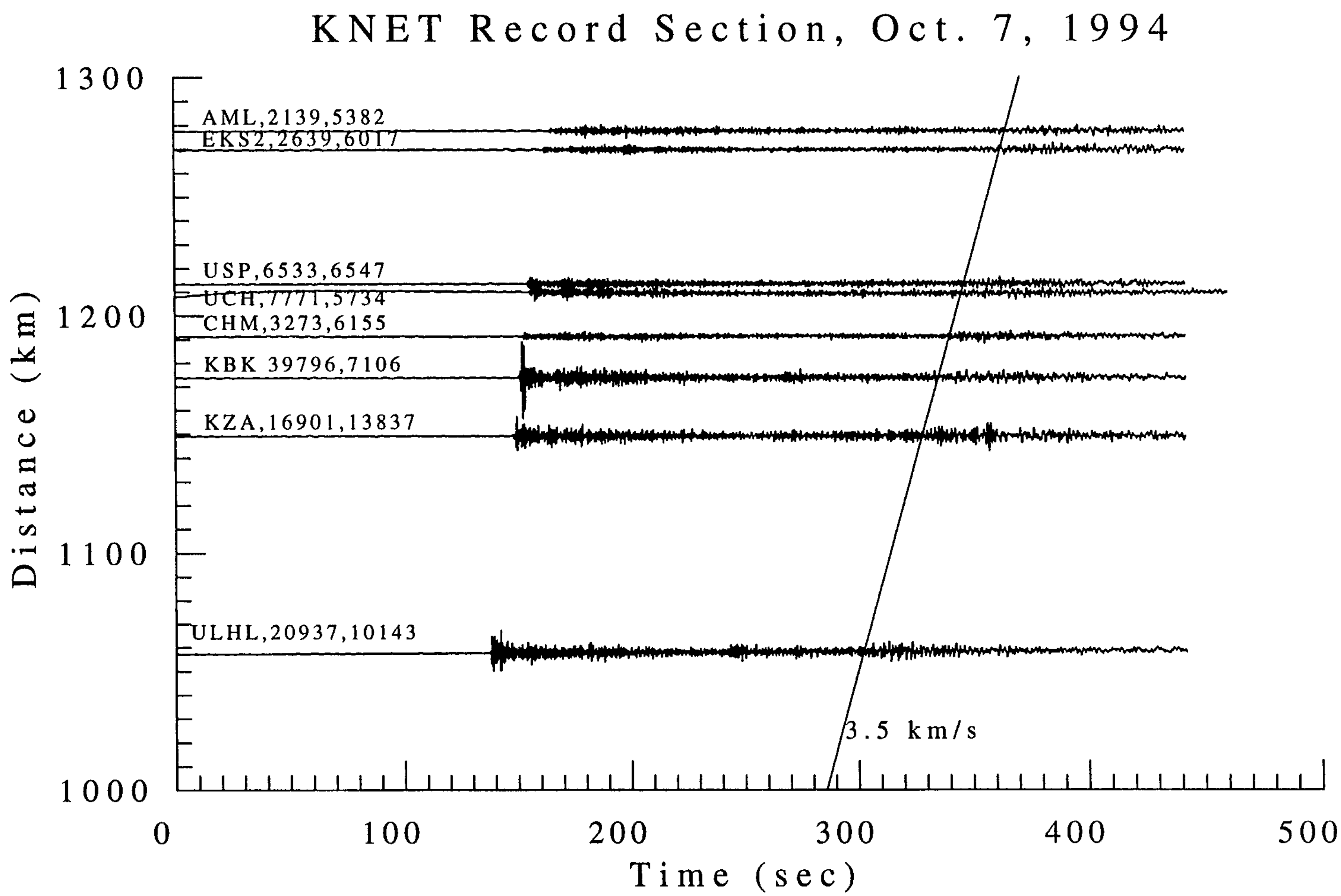

Figure 3. Record section showing seismograms from the Oct. 7, 1994 Lop Nor explosion, at the KNET stations. The first arrival is the Pn phase. The time corresponding to a group velocity of 3.5 km/s (typical of Lg) is marked by a straight line. The traces are normalized by a common factor. Station name and peak Pn and Lg amplitudes are indicated near each trace. Note that at KBK, the amplitude is 12 times of that at a nearby station (CHM), and 19 times of that at station AML.

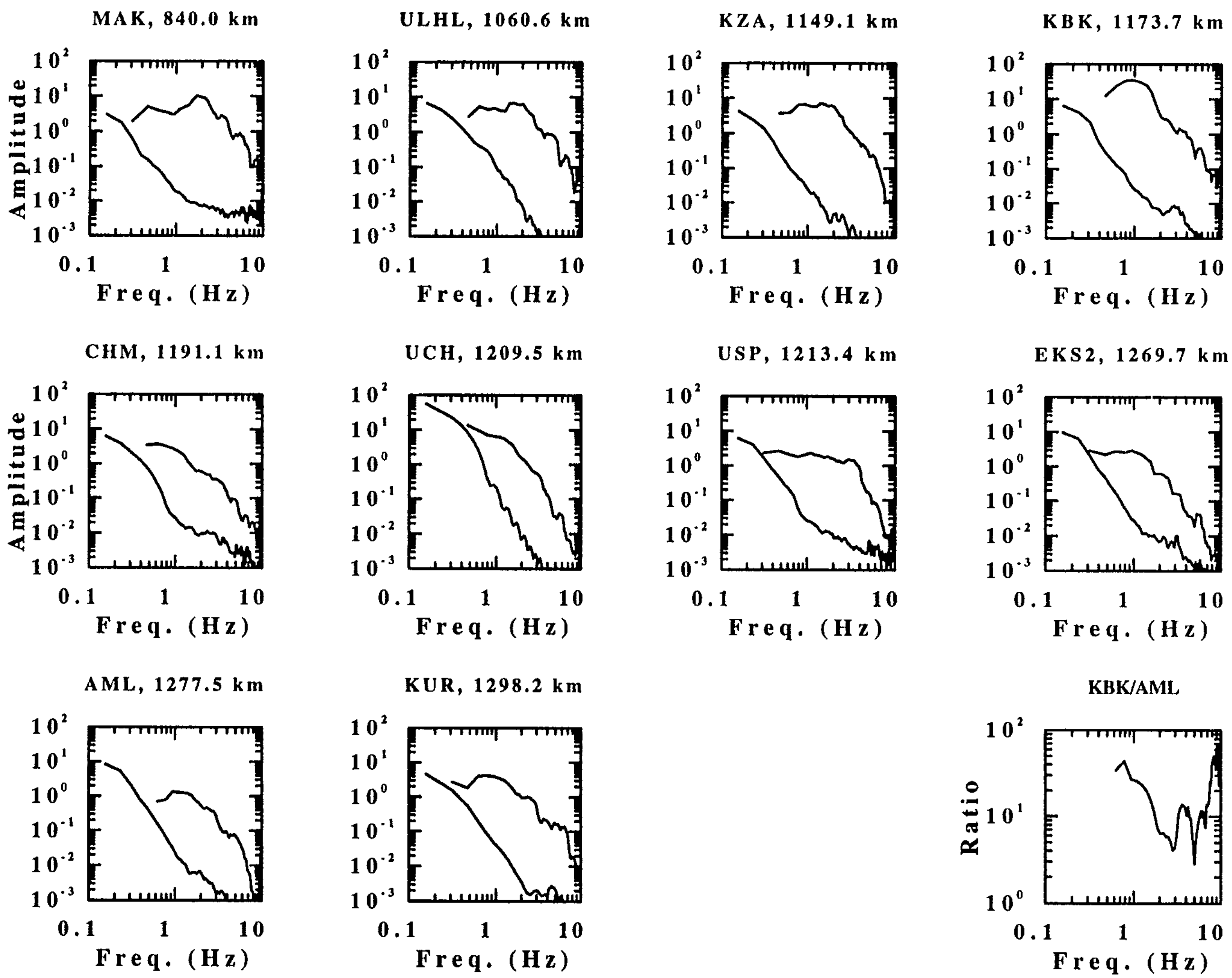

Figure 4. Pn and noise spectra from the Oct. 7, 1994 Lop Nor explosion, calculated for ten KNET and Kazakhstan stations (all but the lower right panels), with an effective window length of 4.5 s. The lower right panel is the spectral ratio of KBK/AML. Note the wide range of the amplitudes at 1 Hz for various stations, and the factor of 27 at 1 Hz in the KBK/AML spectral ratio.

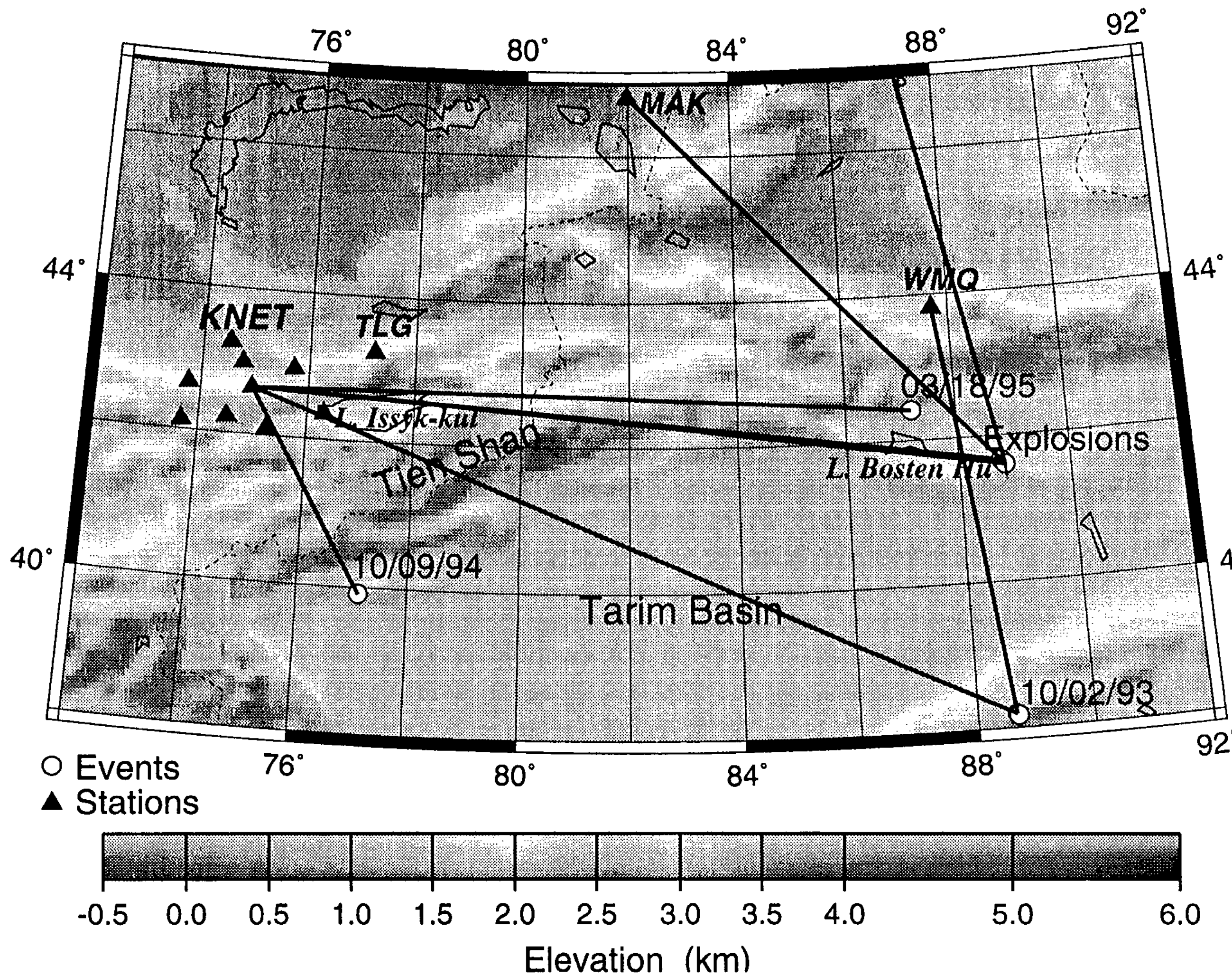

Figure 5. Map showing locations of Lop Nor explosions, an earthquake in northern Xin Jiang (east of Lake Bosten Hu; 03/18/95), and an earthquake in southern Tien Shan (10/09/94). Pn from these three events are presented in this paper as examples. Paths to a representative KNET station (station KBK) are plotted.

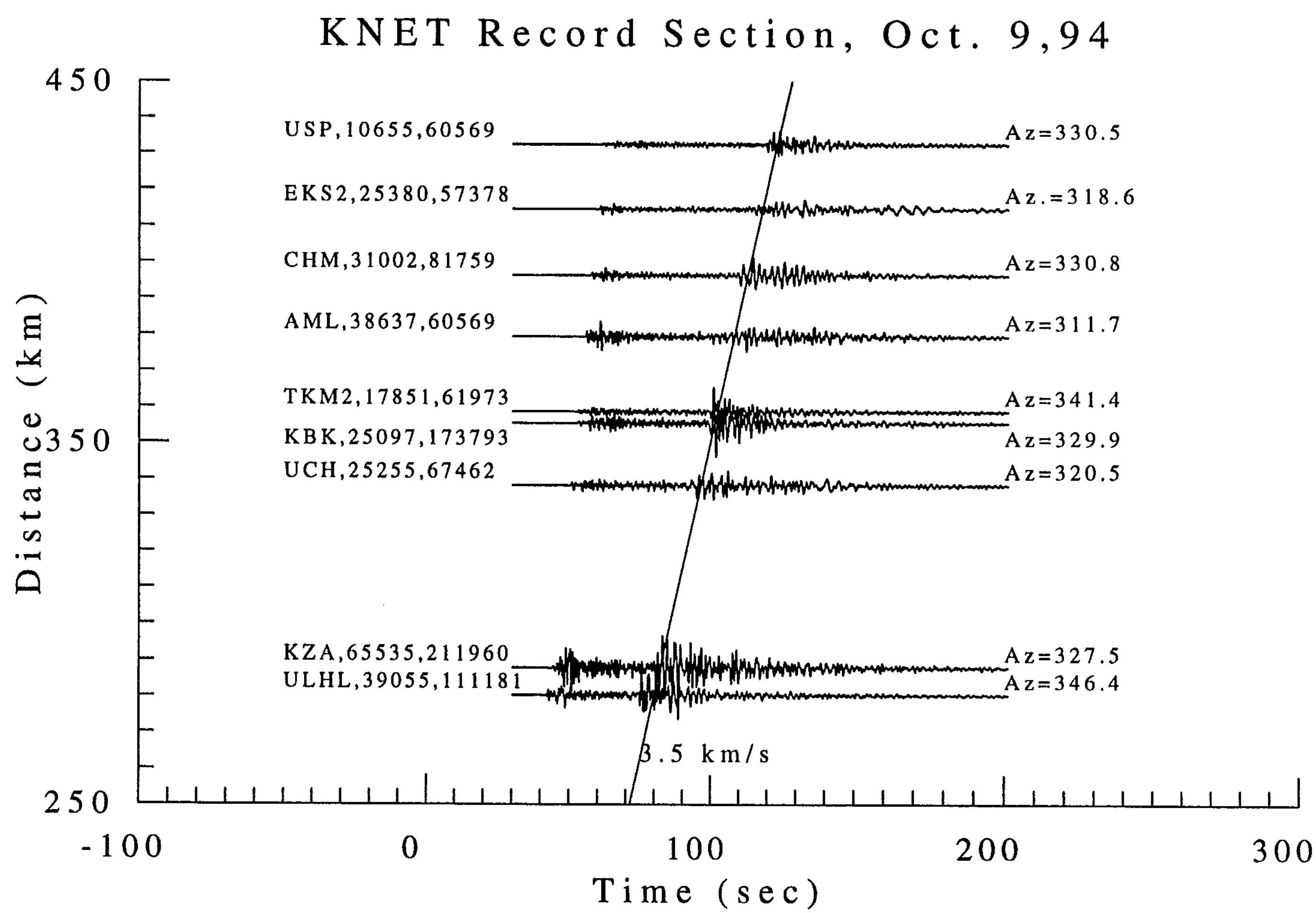

Figure 6. Record section showing seismograms from the Oct. 9, 1994 southern Tien Shan earthquake. The first arrival is the Pn phase. Plotted in the same manner as in Figure 2. Note that the Pn amplitude at KBK is lower than at AML.

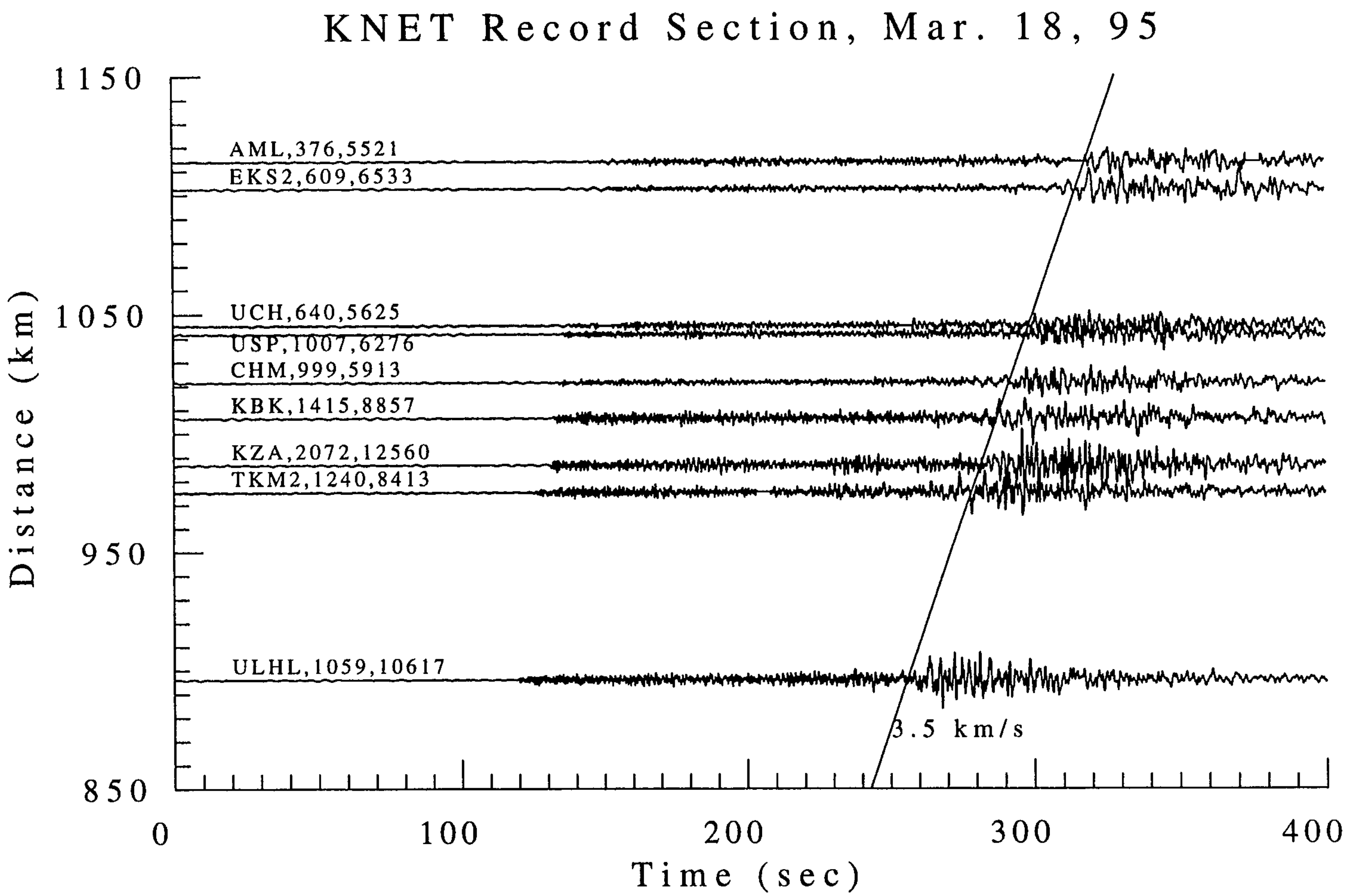

Figure 7. Record section showing seismograms from the March 18, 1995 Northern Xin Jiang earthquake. The first arrival is the Pn phase. Plotted in the same manner as in Figures 2 and 5.

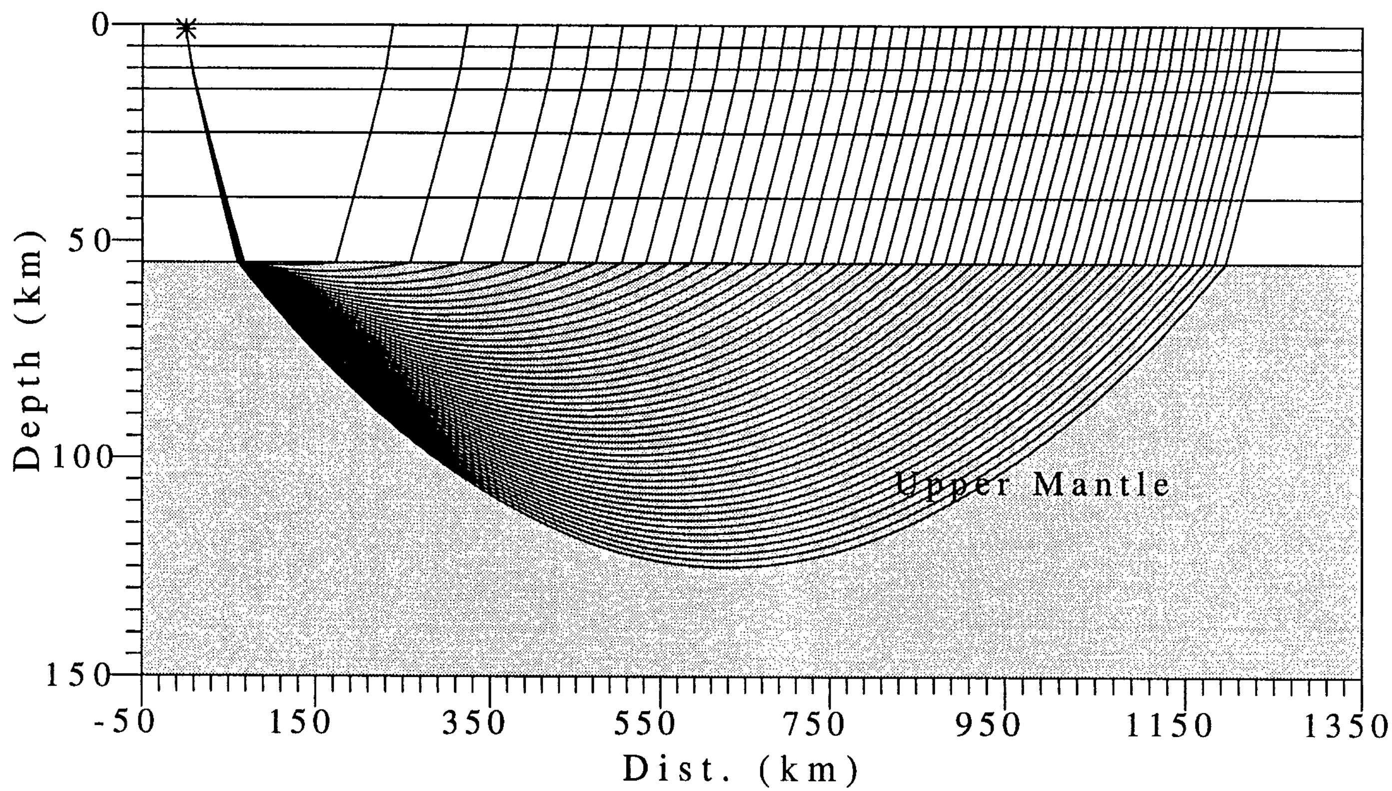

Figure 8. Pn ray pattern for a shallow source (star) in a 1D structure, which is slightly modified from model M1 of Roeker *et al.* (1993) by introducing a zone of a larger velocity gradient (~ 0.002 s^{-1}) below Moho. The ray pattern only serves for a schematic purpose since the velocity gradient used is likely larger than the average value in central Asia.

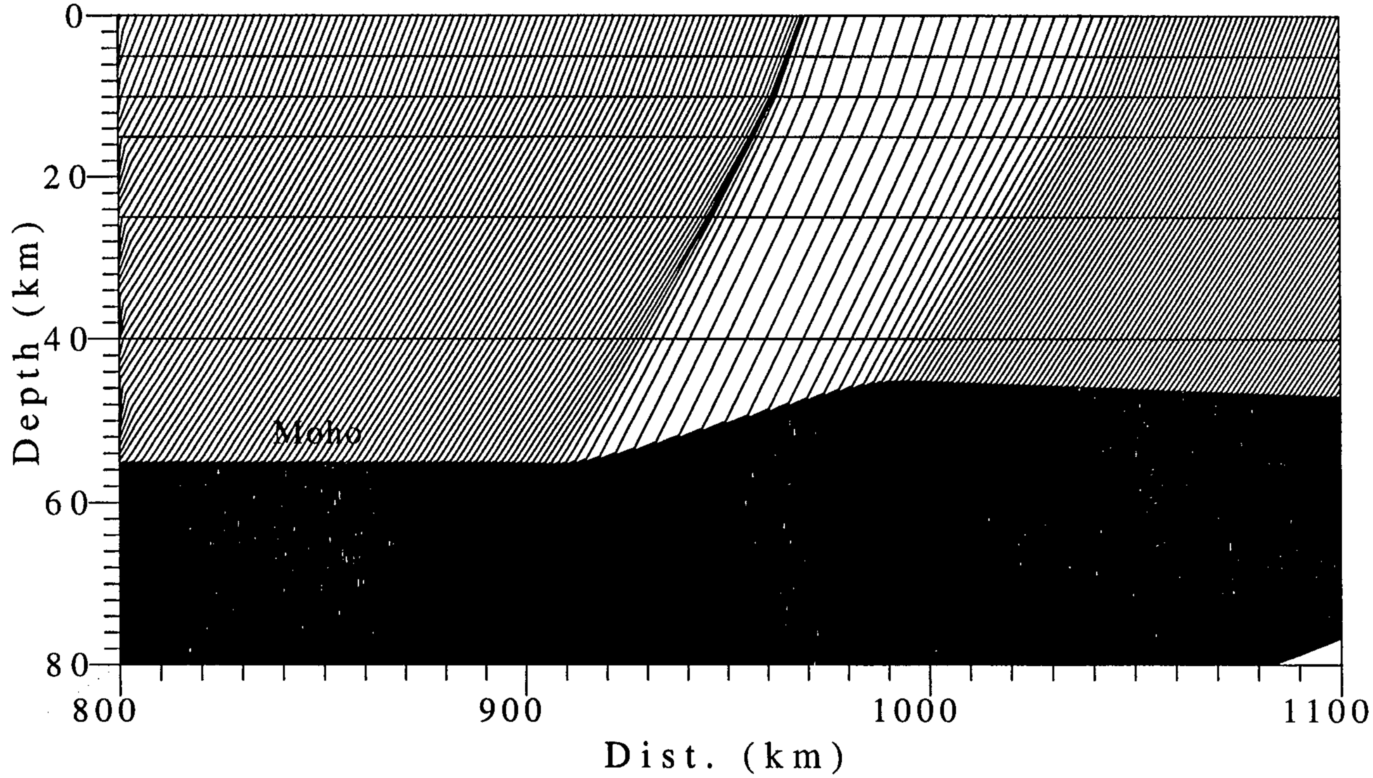

Figure 9. Pn ray pattern in a 2D structure, which is modified from the 1D structure in Figure 8 by by introducing a Moho topography. Between distances of 900 and 1000 km, the Moho depth changes from 55 km into 45 km. Note that with the increasing distance, the ray density shows a pattern of normal-high-low; this corresponds to the observed amplitude variation in Figures. 3, 4 and 7.

introducing a 2D topography to Moho. The depth of Moho in Figure 9 varies from 55 km to 45 km between distances of about 900 and 1000 km. This simple Moho topography results in an amplitude pattern that is qualitatively in agreement with that observed for the explosions and earthquakes from the east of the KNET (Figures 3 and 7): the Pn ray density (which is proportional to the amplitude) remains normal until the distance reaches about 960 km, or some 60 km away from the point where the Moho thinning begins. Pn ray density at around the distance of 960 km increases drastically. As distances further increases, the Pn ray density drops to abnormally low. This example demonstrates how a 2D or 3D Moho topography can drastically change the Pn amplitude. There may be other 3D velocity structures that could produce similar Pn amplitude variations. Any 3D Moho topography responsible for the drastic amplitude variation may well be associated with the drastic variations in surface topography and geology from Lake Issyk-kul to the mountains in the west (Figure 5). Unfortunately, the Pn data that we retrieved so far is not sufficient to uniquely constrain the real 3D structure.

5. PRELIMINARY EVALUATION OF Pn/Lg RATIO AS A DISCRIMINANT

Comparing Figures 3 and 7, one would be tempted to draw an easy conclusion that the Pn/Lg amplitude ratio works well as a discriminant between explosions and earthquakes. However, this conclusion is premature. The reason for the low Pn amplitudes in Figure 7 is likely caused by a null in the source-to-Pn radiation pattern since the earthquakes occurred east of Lake Bosten Hu, where earthquakes sources are typically characterized by an east-west strike-slip motion (Center for Analysis and Prediction, 1991). The earthquakes from southern Tien Shan generate stronger Pn signals across KNET (Figure 6), suggesting that the Pn/Lg ratio from earthquakes is significantly affected by the focal mechanism. Therefore, any attempt to use Pn/Lg amplitude ratio as a discriminant must account for the instabilities of the Pn amplitude (and to a less extent, Lg amplitude) caused by 3D velocity complications, as well as the source-to-Pn radiation pattern. We are currently analyzing Pn from more earthquakes to quantify these instabilities.

6. MEASUREMENT OF M_0, f_c AND PATH Q USING Pn FROM THE OCTOBER 7, 1994 LOP NOR EXPLOSION

In a preliminary analysis, we measured the source and path spectral parameters using Pn from the Oct. 7, 1994 Lop Nor explosion, with the modified algorithm mentioned in a previous section, and the modified Mueller-Murphy source model (Sereno *et al.*, 1988), with an overshoot parameter (β in Eq (2)) of 1.0. Station KBK is not used due to the abnormal large amplitude (Figures 3,4 and 7). The resulting M_0 and f_c values are 3.5 $\times$ 10^{23} dyne-cm and 1.6 Hz, respectively. For comparison, a previous inversion using Lg (Xie *et al.*, 1996) has resulted in an M_0 of 5.5 $\times$ 10^{22} dyne-cm, and an f_c of 0.8 Hz. The averaged Pn Q_0 and η values are 379 and 0.7, respectively, for the nine paths connecting the Lop Nor and stations MAK, ULHL, KZA, CHM, UCH, USP, EKS, AML, KUR. All but the first of these stations belong to the KNET. The lowest and highest Q_0 values are 204 (to station AML) and 573 (to station KZA). Figure 10 shows the synthetic source spectra for that event, versus the observed spectra after path Q correction. The overall fit between the synthetic source spectrum and the station average of the observed (lower right panel) is rather good.

7. SOFTWARE DEVELOPMENT

The computer softwares developed during the last year include:

1. Program "Pn96" which takes the time series containing Pn or any seismic phases, windows the time series between any two specified lapse times or group velocities (adjustable), and calculate Fourier spectra of the windowed phase and noise. It then correct the effect of an specified geometric spreading and reduce the spectra to source. This program is written for studying Pn, Pn coda and Pg, but can be used for studying any regional phases. Figure 11 shows and example of the application of this program.

2. Program "PnQ96" which takes the spectral output of Pn96.f from multiple stations, and searches though all of the possible combinations of M_0, f_c (and thereby $\mathbf{m}$ in Eq (7)) to find the optimal $\mathbf{m}$. The Q_0 and η are allowed to be station-variable. Alternatively, Q_0 and η can be assumed to be station invariant in which case site response, $X(f)$, is assumed to be station-variable. If there is any information on the source spectrum from the EGF method, or on path Q from two-station method, this program incorporate these information during the search. During the search, if negative A''_{ij} in Eq (5) occurs, this program finds Q_{0i} and η_i by an interactive, non-linear algorithm.

3. A set of programs that finds the average two-station Q using spectral output of "Pn96" by stacking spectral ratios for all pairs of two stations available.

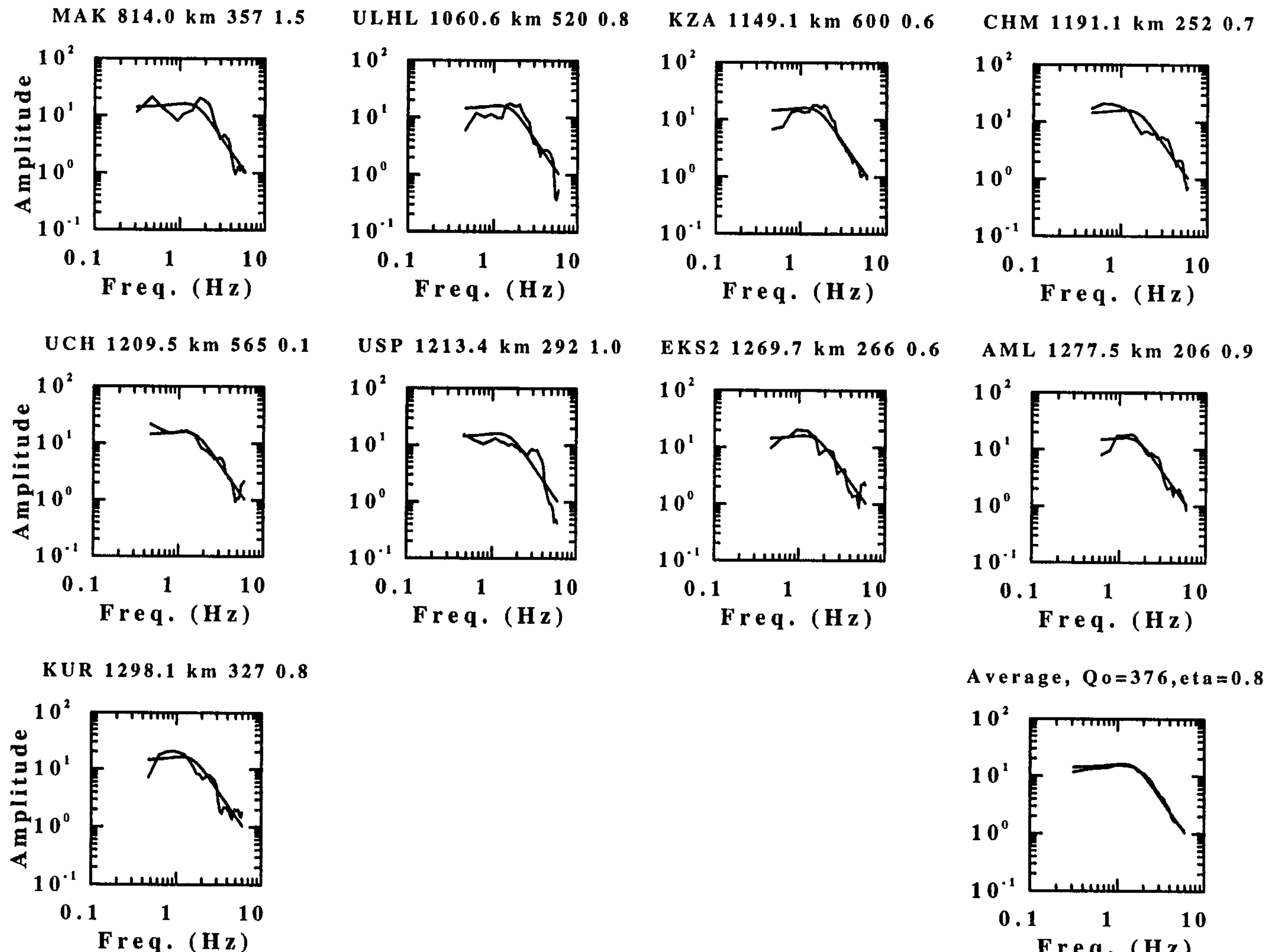

Figure 10. Synthetic Pn source spectra for KNET and IRIS stations recording the Oct. 7, 1994, Lop Nor explosion, versus the observed. The lower right panel is the station average. The synthetic spectra are calculated using a β of 1.0 and the optimal source spectral parameters ($M_0 = 3.5 \times 10^{23}$ dyne-cm, f_c=1.6 Hz) obtained in the inversion. The distance, Q_0, η and values are written on the top of the panels. The unit of the amplitude is the same as that of Figure 3 of Xie *et al.* (1996).

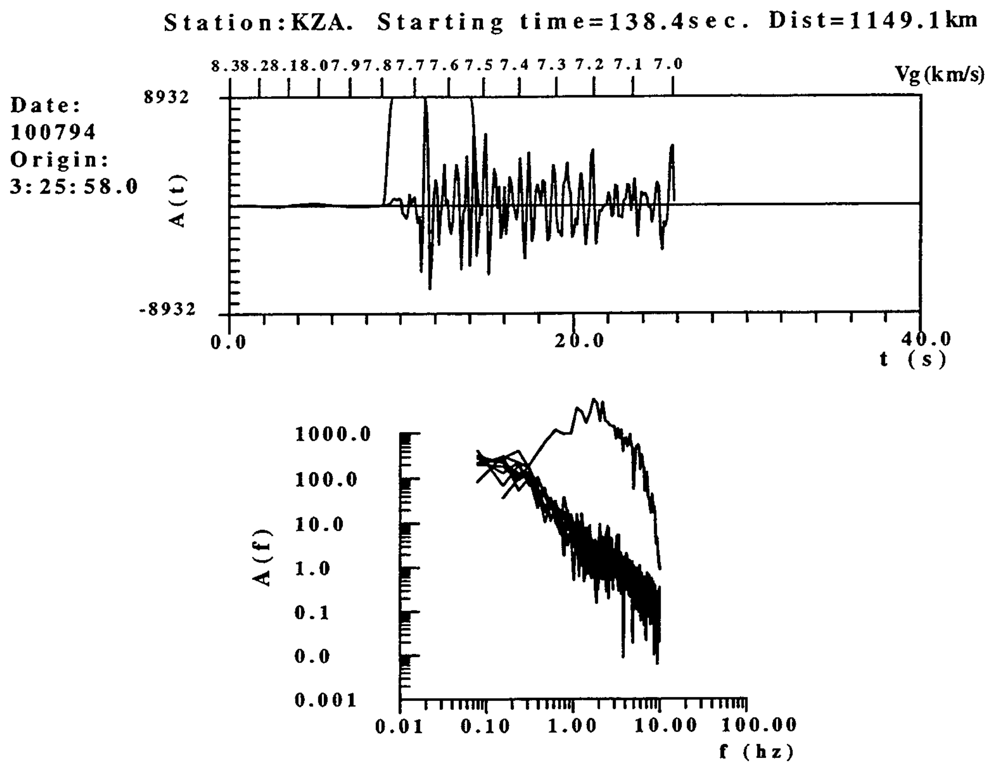

Figure 11. An example of the application of program Pn96. The top panel is the time series containing Pn from a Lop Nor explosion at a KNET station. Group velocities and time after the beginning of the window are indicated on the top and bottom of the panel. The smooth curve represents a 20 percent cosine window used in the analysis. The bottom panel show the Fourier amplitude spectra of Pn and noise.

8. CONCLUSIONS AND FUTURE WORKS

Much of the first year of this research has been devoted to software development, data collection and processing, and synthetic studies of the Pn propagation. Several important findings have been made on the characteristics of Pn excitation and propagation in central Asia. These include:

(1) Two modifications to the spectral inverse algorithm of Xie (1993) serves well to improve our ability to seek for more reliable and robust estimates of source M_0, f_c and path Q_0, η values using regional wave spectra.

(2) Pn geometrical spreading estimated using synthetics in 1D structures for central Asia suggests that it agrees roughly with a trend of $\Delta^{-1.3}$, although the localized fluctuation is quite significant (by a factor of 2 or more) from that trend.

(3) The observed Pn amplitude varies drastically (by a factor of up to 20 to 30) across KNET from Lop Nor explosions and Northern Xinjiang earthquakes, which are located to the east of the stations. This amplitude variation primarily occurs at lower (~ 1 hz) frequencies, and does not correlate with the amplitude variation across KNET from events in the south. The most likely cause of the amplitude variation is a short wavelength variation in the Moho topography.

(4) Pn/Lg amplitude ratio also appears to be highly dependent on the source-to-Pn radiation pattern. This ratio can be used efficiently to identify earthquakes when the station is located at the Pn radiation null. For other source-station configurations, however, the efficiency of the ratio as a discriminant between explosions and earthquakes needs further investigation.

(4) Preliminary inversion of a well-recorded Lop Nor explosion suggests that the M_0 and f_c values derived using Pn are both higher than those derived using Lg. Inversion of Pn spectra from many more events, with an improved method, is underway.

Research conducted so far suggests that any attempts to use Pn/Lg amplitude ratio as a discriminant, or to invert for source/path spectral parameters must take into account the Pn amplitude variations caused by effects of 3D velocity complications and the source radiation pattern. Since both effects are supposed to be reduced when Pn coda is used, we have already implemented an algorithm to invert for M_0, f_c, path Q_0 and η using the entire wavetrain that includes Pn, Pn coda and/or to Pg. We will compare the stability of the results using Pn alone with those using the averaged spectra of Pn and Pn coda. Since almost all necessary software development has been achieved, the next phase of the research will be mainly devoted to data processing, inversion and interpretation.

By collecting Pn records at KNET stations from more Northern Xinjiang earthquakes, particularly those earthquakes whose focal mechanisms differ from the typical east-west strike slip, we will continue to explore the cause for the large Pn amplitude variation across the KNET for the east-west oriented paths. In particular, the existence of

any 3D Moho topography and its link to the topographic/geological variation from Lake Issyk-kul to Northern Tien Shan will be investigated.

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